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INVESTIGATION OF FRICTION LOSS CHARACTERISTICS OF ENGINE PISTONS FOR DIFFERENT ENGINE OPERATING CONDITIONS

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ABSTRACT–In this study, the floating liner method is utilized to measure the friction generated in the piston assembly of a single-cylinder gasoline engine. The piston assembly is subjected to combustion pressure, lubricating friction, and asperity friction during engine operation and reciprocates within the cylinder. Therefore, the main goal of this study is to investigate the effect of engine combustion and lubricant conditions on piston friction. First, we analyze how the combustion pressure, obtained by changing the combustion load and the ignition timing, affects piston friction. Second, by adjusting engine speed and coolant/oil temperature, we analyze how each condition affects piston friction. Through the experiments for each case, it was confirmed that the friction increased as the combustion pressure increased under the same lubrication conditions. It was also confirmed that the piston friction was significantly measured due to the increase in lubrication friction as the engine speed increased. Finally, it was confirmed that as the temperature decreased, the oil viscosity increased, resulting in a large friction loss.

KEY WORDS : Gasoline engine, Piston friction, Floating liner method, Lubricant, Combustion condition

1. INTRODUCTION

The automobile industry is conducting various research in stages such as high-efficiency engine development and hybrid car development intending to develop eco-friendly vehicles, to meet the increasingly strengthened environmental regulations. Energy gained through combustion in an engine is lost due to various factors, such as heat loss and mechanical loss. Therefore, it is important to reduce these losses to develop a high-efficiency engine. Considering that friction loss accounts for about 4 to 15 % of the energy obtained from fuel and brake horsepower accounts for about 30 to 40 %, it can be seen that the contribution of friction loss to combustion efficiency is rather large. Among the friction losses of an engine, the friction of moving system parts related to power transmissions, such as piston assembly, crankshaft, and camshaft, accounts for about 47 to 58 % of the total. And these parts are affected by the lubrication condition of the engine. Therefore, to analyze the friction of these parts, engine operating conditions such as combustion, lubrication, temperature, and speed must be considered. Therefore, in this study, the change of piston friction by condition was analyzed by controlling the driving conditions of the combustion engine.

Various studies have been conducted to reduce energy loss to develop a high-efficiency engine. Lee *et al*. (2022) showed that the heat loss of the cylinder was reduced by about 13 % by using the lean-stratified charge (LSC) mode, and the indicated thermal efficiency (ITE) was about 34 %, especially under the low load condition. To reduce energy loss in diesel engines, Okamoto and Uchida (2016) installed multiple fuel injectors to reduce heat loss and emissions. Aghaali and Ångström (2015) suggested the possibility of realizing high-efficiency engines by recovering exhaust heat through turbo-compound technology. Xu *et al*. (2016) proposed a way to improve engine performance through intake valve control using electromagnetic intake valve train (EMIV) technology. Truong *et al*. (2013) developed analytical modeling for a variable-displacement vane-type oil pump to derive a performance improvement plan. Benajes *et al*. (2016) analyzed the effect of piston bowl geometry on heat transfer and energy loss in reactivity controlled compression ignition (RCCI) combustion. The analysis showed that the reduction of the piston surface area can significantly reduce heat loss. Tormos *et al*. (2018) developed friction models to reduce friction losses. A detailed description of the analysis model for calculating the friction of each engine part was provided.

The friction generated in the engine is divided into two types: mechanical friction caused by major parts such as piston, crankshaft, and valvetrain, and friction caused by

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auxiliary equipment such as pumps, drive-belt, and cooling fans (Hoshi, 1984). Since the friction generated by the piston accounts for about 20 ~ 30 %, it is important to study the friction reduction of the piston. Yin *et al*. (2020) conducted a study on the double bump design of the main thrust side of the piston for friction and wear performance through dynamic modeling and four-cylinder diesel engine experiments. Grabon *et al*. (2017) conducted friction experiments using various surface textures of cylinder liners. It was confirmed that the frictional resistance increased as the honing angle increased. Usman and Park (2016) analytically derived the possibility of reducing friction loss through surface treatment of piston rings. Especially in the warm-up process, where engine efficiency is significantly reduced, the surface-treated piston rings have resulted in a significant reduction in energy loss. Jang (2022) investigated in detail the hydrodynamic lubrication film formation and pressure between the piston ring and cylinder liner at the top dead center (TDC) position. The surface roughness of the cylinder liner by the honing process similar to the thickness of the lubricant film at the TDC position was considered. Duarte Forero *et al*. (2020) analyzed the effect of the geometrical profile of a piston ring on lubricating friction. By improving the profile of the compression ring, friction loss was reduced by about 21 %, and the lubrication performance was improved by thickening the lubrication film. Totaro *et al*. (2016) improved engine performance by modifying the profile of the piston skirt. Improvements to the piston skirt have reduced solid-solid contact friction, reducing friction losses by approximately 12 %. Jiang *et al*. (2015) studied the three-dimensional EHD lubrication and wear loss of piston ring-cylinder liner components for five rings of a combustion diesel engine using the VC++ program. Parameters such as gas blow-by, variable density, the viscosity of the lubricant, surface roughness, friction heat flux, and normal elastic deformation were considered in the EHD lubrication analysis algorithm. Most of the research has focused on reducing lubricating friction and asperity friction to reduce the friction in piston assembly. The piston in the combustion chamber performs reciprocating linear motion by achieving a balance of force by combustion pressure, lubricant friction, asperity friction, side force, and connecting rod force (Zhu *et al*., 1992). Therefore, in this study, how the combustion conditions of the engine affect the piston friction was investigated. We analyzed how each factor affects friction through piston friction measured when combustion pressure, engine temperature, and speed are varied by controlling combustion conditions.

There are several experimental methods for measuring engine friction. The strip-down method is a method of measuring the difference in driving torque caused by removing or replacing a specific part of the engine as the friction of that part (Krishnan, 2014). It has the advantage of being able to measure the detailed friction of each part, but the experiment can only be conducted under motor conditions without combustion. The floating liner method is a method that can directly measure the frictional force applied to a cylinder through load cells mounted on the cylinder using a single-cylinder engine (Sato *et al*., 2015). It has the advantage of being able to measure the friction of the piston assembly that occurs under the driving conditions of an actual engine. However, the accuracy of the structural design to pack the cylinder pressure generated during the combustion process is critical. The IMEP method is a method of measuring the friction acting on a piston by mounting a strain gauge on the connecting rod and measuring the force applied to the connecting rod (Carden *et al*., 2006). Although it has the advantage of being able to directly measure piston friction through combustion pressure and the force of the connecting rod, it has the disadvantage that the precision of the combustion pressure and connecting rod measuring sensor is important. Consequently, in this study, the friction of the piston assembly was directly measured under combustion conditions by adopting the floating liner method. Four load cells are installed at the bottom of the cylinder of a single-cylinder engine, and friction is obtained by averaging the data of the four load cells to offset the side force applied to the cylinder. In addition, by balancing the combustion chamber pressure through the O-ring mounted on the cylinder, the error in data acquisition is minimized.

2. METHOD

2.1. Analysis of Factors Affecting Piston Friction

In this study, the force applied to the engine piston was summarized through the schematic diagram shown in Figure 1. The piston in the combustion chamber is balanced through four types of forces: the force of the connecting rod, the force of the combustion pressure, the lubricant friction, and the asperity friction. The behavior of the piston can be analytically calculated through the force balance equation and the moment equation due to the forces applied to the piston (Zhu *et al*., 1992). The piston friction can be calculated analytically by considering detailed factors such as piston eccentricity, surface roughness, and weight. As a result, the frictional force between the piston and the cylinder is affected by the cylinder pressure and the lubricant condition. Therefore, we analyzed the effect of combustion pressure and lubricant condition on piston friction by varying engine combustion conditions.

As shown in the Stribeck curve in Figure 2, the characteristics of lubricating friction are determined through parameters such as lubricant viscosity, velocity between objects, and normal force (Delprete and Razavykia, 2020). Since the viscosity of lubricants is strongly affected by temperature, controlling the coolant/oil temperature is very important in lubrication friction experiments. The normal force between two objects is determined by the

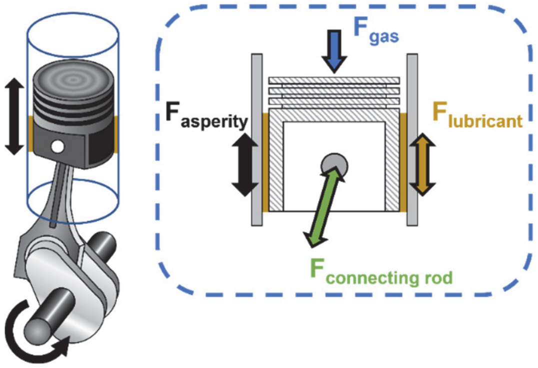

Figure 1. Schematic diagram of the force equilibrium acting on the engine pistons.

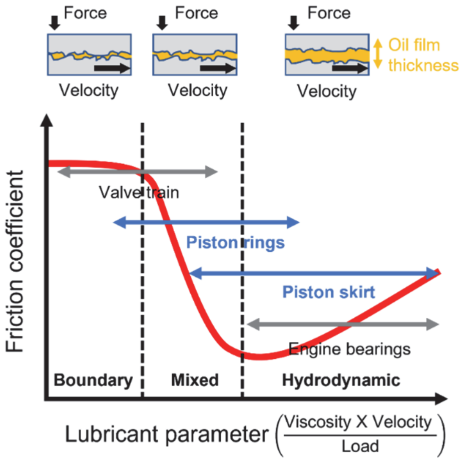

Figure 2. Lubrication regime for each engine component by Stribeck curve.

roughness between the objects and the thickness of the lubricant. Therefore, in this study, it was analyzed whether the characteristics of lubrication friction appeared through the adjustment of engine speed and coolant/oil temperature.

Combustion pressure is affected by several factors such as ignition timing, fuel injection quantity, and injection timing. Indicated mean effective pressure (IMEP), which is used as an indicator of the combustion load of the engine, can be calculated from the combustion pressure. In this study, the effect on friction by increasing the combustion load was analyzed. In addition, we analyzed the friction force when the combustion pressure changes by varying the ignition timing under the same load condition.

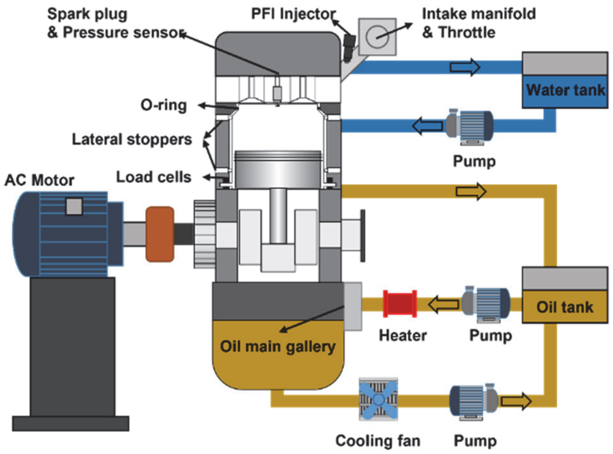

Figure 3. Experimental schematic diagram of floating liner engine.

Table 1. Specifications of floating liner engine.

Engine type	Single-cylinder floating liner
Bore (D)	81 mm
Stroke ($2r$)	97 mm
Connecting rod length (l)	150 mm
Friction data acquisition	Load washer 9011A
Fuel injection	Gasoline PFI injector
Engine oil	SAE 5W-20

2.2. Experimental Setup to Measure Piston Friction under Combustion Conditions

To measure the piston friction, the floating liner method was performed on a gasoline engine in this study. The floating liner method is an experimental method that can directly measure cylinder friction through four load cells mounted on the lower part of the combustion chamber cylinder. A schematic diagram of the engine used in the experiment can be seen in Figure 3. Experiments were conducted with a single-cylinder engine with a bore of 81 mm and a stroke of 97 mm. The detailed specifications of the single-cylinder engine are shown in Table 1.

The engine coolant/oil was circulated through the pump using an external temperature control system. Since the friction force of the piston assembly is greatly affected by temperature, the coolant/oil temperature was adjusted by controlling the cooling fan and heater of the external control system. The temperatures were measured through thermocouples mounted on the inlet and outlet of the engine coolant/oil. And after calculating the average of the inlet and outlet temperature, data for each experimental condition were acquired within ± 0.1 °C of the target temperature. The engine speed was kept constant at the target speed via a motor connected to the engine. Variable conditions such as fuel injection amount, injection timing, and ignition timing for engine combustion were controlled using a data acquisition device with NI LabVIEW software. The engine air-fuel ratio was maintained at 1.0 under all experimental conditions. In addition, to ensure combustion stability, data were acquired after maintaining the combustion conditions for 30 minutes before data acquisition. The combustion chamber pressure and the load cell data were also acquired through the same LabVIEW software. The experimental data were obtained one per 0.2° crank angle, and one cycle of 720° based on the top dead center was obtained continuously. As a result, the average value of 100 cycles data was derived as the result value through the data post-processing process.

Experimental variables were set in four types: temperature, speed, combustion load, and ignition timing. The base experimental conditions were 80 °C, 1000 RPM, 400 kPa, and before top dead center (BTDC) 15°, respectively. In this study, the temperature was set to 50 ~ 80 °C (10 °C intervals) because it is difficult to control the variable due to the high combustion heat in the low-temperature condition. The speed was set from 1000 to 1600 RPM (200 RPM intervals) because of the problem of increased experimental deviation due to vibration occurring in high-speed conditions. Due to combustion instability, the combustion load was set from 400 to 475 kPa (25 kPa intervals), and the ignition timing was set from BTDC 17° to BTDC 11° (2° intervals).

3. RESULTS AND DISCUSSION

3.1. Effects of Combustion Pressure on Piston Friction

To confirm the change in piston friction due to combustion pressure, the experiment was conducted by changing the combustion load and ignition timing. First, the experiment was performed with only the combustion load conditions changed, and the combustion pressure for each condition is shown in Figure 4. To increase the combustion load with other variables fixed, the experiment was conducted by increasing the fuel injection quantity and intake air volume. As shown in Figure 4, the higher the combustion load, the greater the combustion pressure. The friction data obtained from the experiments can also be seen in Figure 6, and it shows the friction data acquired using the load cell and the power loss calculated by the friction force. The power loss of the piston is expressed as the product of the friction force and the instantaneous speed of the piston, and Figure 5 shows the vertical speed of the piston under the condition of 1000 RPM for each crank angle. The formula for calculating the instantaneous velocity and instantaneous power loss of the piston is as follows:

$$v_{piston}(\theta) = r\omega\left[\sin\theta + \frac{\sin\theta}{2\sqrt{(l/r)^2 - \sin^2\theta}}\right] \tag{1}$$

$$P_{friction}(\theta) = F_{friction}(\theta) \times v_{piston}(\theta) \tag{2}$$

where r is the half stroke (= crank rotation radius), l is the length of the connecting rod, and ω is the engine speed. As can be seen from the friction force measurement results in Figure 6, it can be seen that the friction force increases in the compression stroke as the combustion load increases. Similar frictional forces were measured for the rest of the stroke. The speed of the piston was kept the same as shown in Figure 5. For this reason, the power loss of the piston was calculated as a larger value as the combustion load increased in the compression stroke, and similarly calculated in the rest of the stroke. The power loss is used to calculate frictional friction mean effective pressure (FMEP), an indicator of friction loss in engine performance. The FMEP results by combustion load can be compared using Figure 7, and the FMEP calculation formula is as follow:

$$FMEP = \frac{\int F_{friction} v_{piston}\, d\theta}{V_d} \tag{3}$$

where V_d is the combustion chamber volume. It can be seen that the FMEP increases as the combustion load increases.

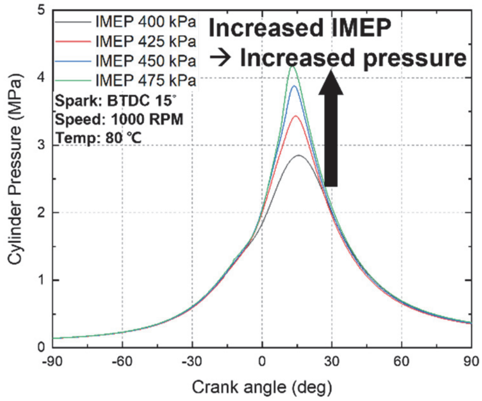

Figure 4. Combustion pressure measurement result by combustion load.

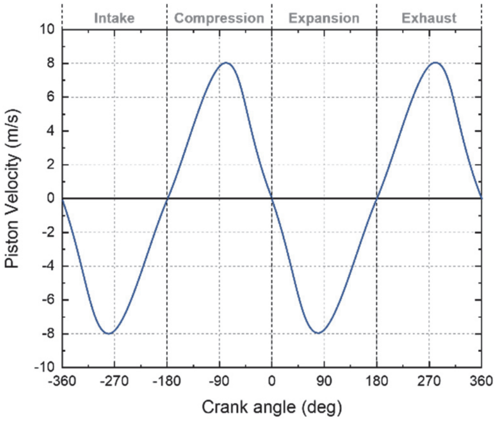

Figure 5. Piston velocity at engine speed 1000 RPM.

As a result, the higher the combustion load, the greater the combustion pressure is applied to the piston, resulting in greater friction force. Considering that there is little change in piston friction in the intake and exhaust stroke that is hardly affected by combustion pressure, it is analyzed that combustion pressure has a proportional effect on piston friction.

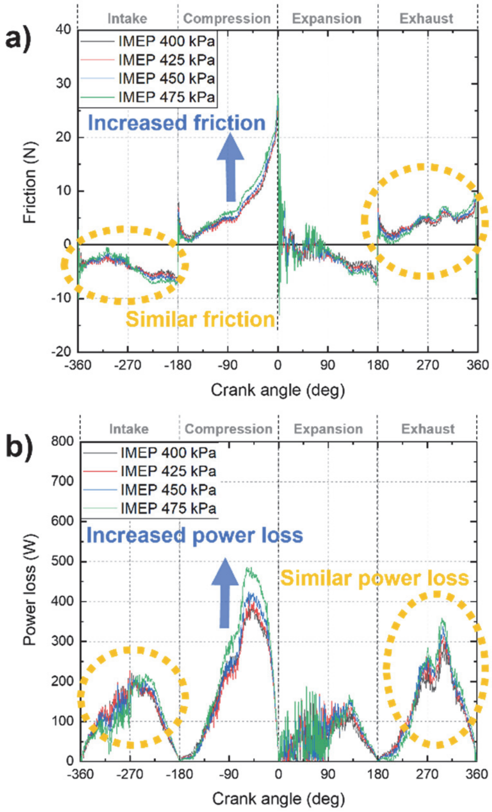

Figure 6. Comparison of a) Piston friction and b) Power loss due to increased combustion load.

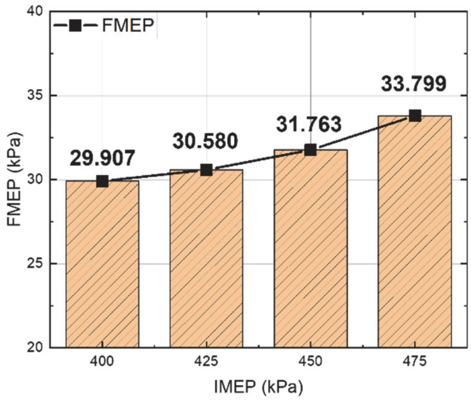

Figure 7. FMEP calculated from friction force by combustion load.

Second, the combustion experiment was conducted by setting the ignition timing differently. To change the ignition timing while setting the combustion load to the same 400 kPa, the experiment was performed by adjusting the amount of fuel and intake air as well. The combustion pressure results for each ignition timing can be found in Figure 8, and it can be seen that the combustion pressure

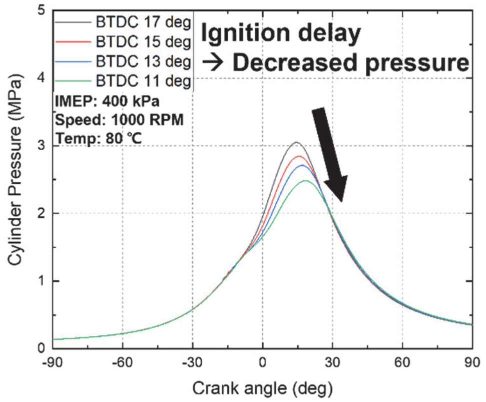

Figure 8. Combustion pressure measurement result by ignition timing control.

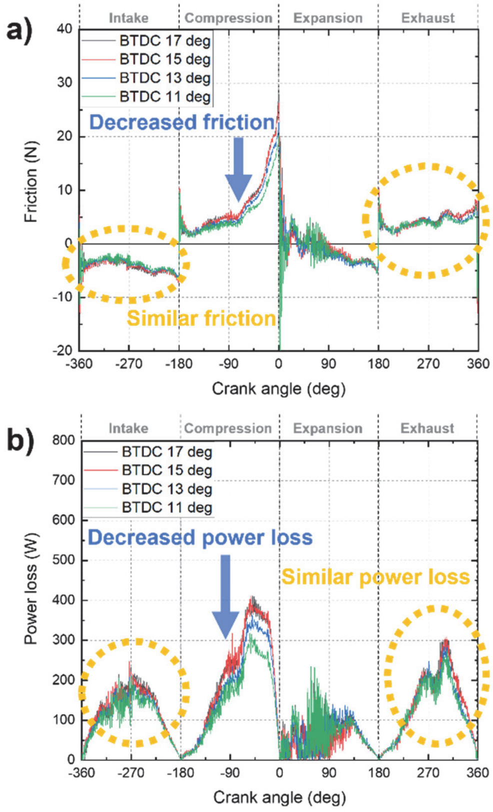

Figure 9. Comparison of a) Piston friction and b) Power loss due to ignition delay.

decreases as the ignition is delayed. The friction results by ignition timing can be seen in Figure 9. Similar to combustion load conditions, it can be seen that the friction changes in the compression stroke where the combustion pressure is affected, and there is little friction change in the intake and exhaust strokes. It can be seen that the piston friction decreases as the ignition timing is delayed compared to the base condition of BTDC 15°. Due to this, the power loss of the piston is also calculated to be small in the compression stroke as the friction force decreases while maintaining the condition of the 1000 RPM piston speed. The results of the FMEP calculation can be found in Figure 10, and the FMEP decreases as the ignition timing is delayed. In conclusion, it can be confirmed that the combustion pressure is reduced due to the retardation of the ignition timing, and the piston friction is reduced. However, delaying the ignition timing with the combustion load fixed at 400 kPa consumes more fuel than before, so it is inefficient in terms of engine efficiency.

In summary, it is analyzed that combustion pressure has a proportional effect on friction, as can be seen through the experiments of the two cases. Two identical phenomena were observed in both cases. The first is the change in piston friction caused by the combustion pressure in the compression stroke where the combustion pressure is largely applied. As can be seen in both cases, friction increases when combustion pressure increases, and friction decreases when combustion pressure decreases. The second is the similarity of piston friction in the intake and exhaust strokes with little effect on combustion pressure. In both cases, the lubrication temperature and engine speed were kept the same, so the lubricant friction is applied equally. And the combustion pressure is almost the same. Therefore, it can be concluded that combustion pressure is a factor that has a proportional influence on piston friction.

3.2. Effects of Lubricant Conditions on Piston Friction

To determine the change in piston friction due to lubricant conditions, the engine speed and coolant/oil temperature were set as experimental variables in this study. The combustion load and the ignition timing were set to be the same as the base conditions. First, combustion experiments were conducted with different engine speeds, and the amount of fuel and intake air was adjusted for each condition. The combustion pressure measured for each speed is shown in Figure 11. The same combustion load conditions were maintained, but not the same combustion pressure due to changes in engine speed. As the engine speed increases, the combustion pressure tends to decrease. The friction for each condition is shown in Figure 12. From the piston friction results at the top of the figure, it can be seen that the friction increases in the intake and exhaust strokes as the engine speed increases. However, it can be seen that almost similar friction was measured on the compression stroke. It is assumed that this result is derived from the combination of the friction increase due to the increase in speed and the friction decrease due to the decrease in combustion pressure. The power loss at the bottom of the figure shows an increase in all strokes due to an increase in engine speed, and this result is derived because power loss is expressed as the product of friction and speed. The FMEP results as a function of engine speed can be seen in Figure 13. Similarly, it can be seen that the FMEP also increases as the engine speed increases. As a result, it was analyzed that the lubrication friction increased due to the increase of the piston speed, and thus the piston friction increased. However, the exact effect of lubricant friction could not be analyzed because of the problem that the combustion pressure was not the same in the speed variable, but the next experimental variable, temperature, could solve this problem.

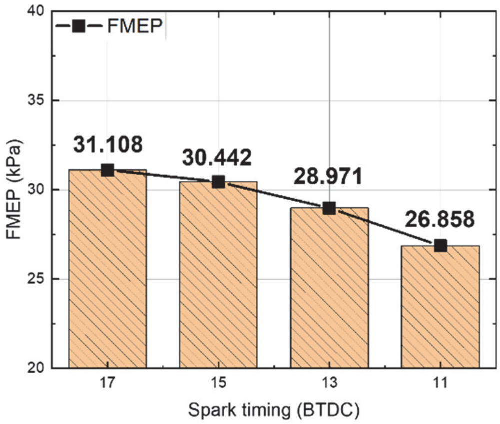

Figure 10. FMEP calculated from friction force by ignition delay.

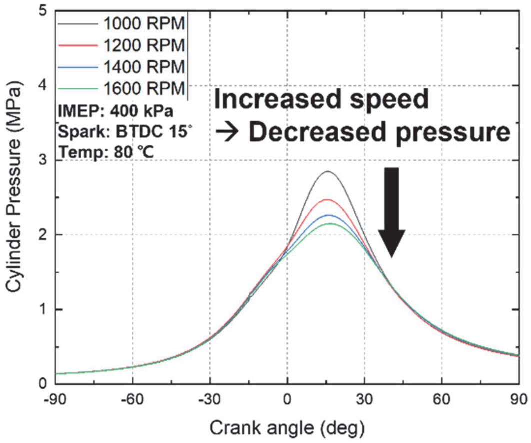

Figure 11. Combustion pressure measurement result by engine speed.

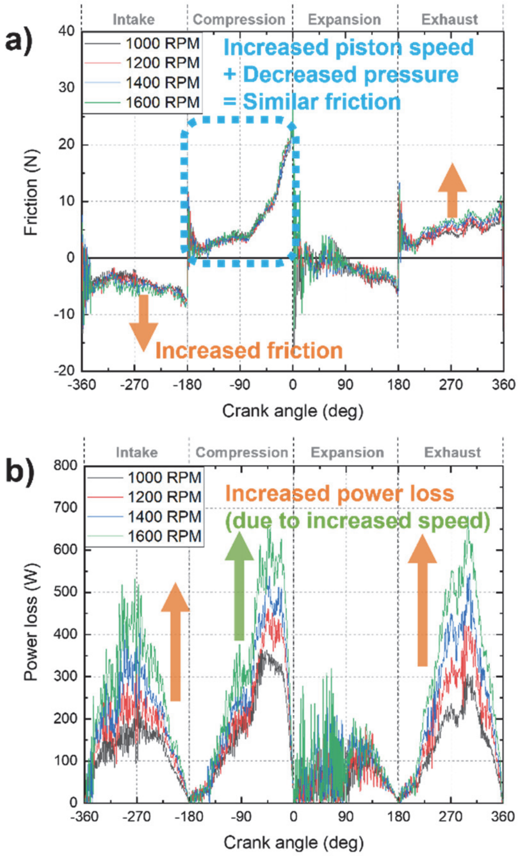

Figure 12. Comparison of a) Piston friction and b) Power loss due to increased piston speed.

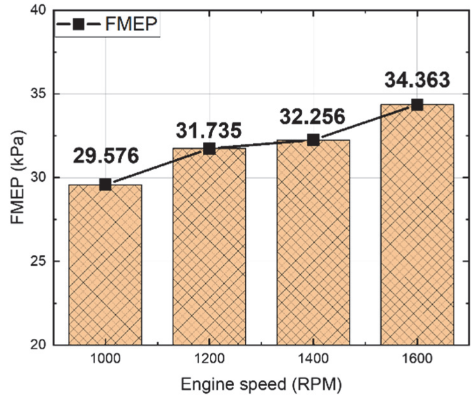

Figure 13. FMEP calculated from friction force by engine speed.

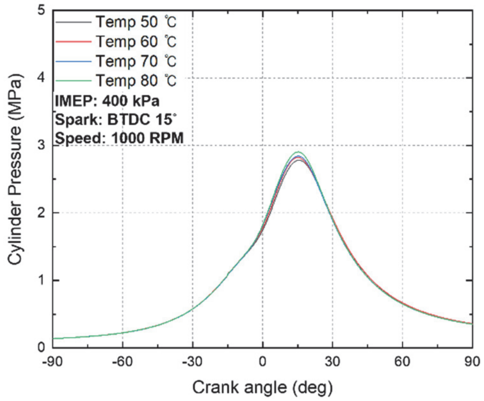

Figure 14. Combustion pressure measurement result by coolant/oil temperature.

Second, the combustion experiments were conducted by varying the temperature of the coolant/oil supplied to the engine. The combustion pressure results acquired through the combustion experiments are shown in Figure 14. In the case of combustion experiments in low-temperature conditions, there were some difficulties in maintaining the temperature. Due to the high heat of combustion, it was difficult to maintain the low-temperature condition, so the deviation between the IMEP and the fuel injection amount was found to be up to 2 %. However, as a result of the comparison of combustion pressure, it was confirmed that similar measurements were made under all temperature conditions. For this reason, it was judged that the combustion pressure was not affected. Therefore, it was possible to analyze the effect of lubrication friction on the piston through the temperature variable. Figure 15 shows the friction obtained from the combustion experiment and the power loss calculated from the friction. Figure 15 shows that the friction decreases with increasing temperature at 50 °C. The power loss shows the same trend as friction, and Figure 16 showing the FMEP calculation results also shows the same trend. As a result, it was analyzed that the higher the coolant/oil temperature, the lower the viscosity of the lubricating oil, thereby reducing the lubricating friction. It is presumed that the increased friction at lower engine temperatures is the reason why the engine's efficiency decreases under cold start conditions of the engine.

In summary, through experiments on two variables that affect lubrication friction, we could confirm the characteristics of lubricant friction. As can be seen from the Stribeck curve in Figure 2, the engine speed and the lubricant friction are in a proportional relationship, and oil viscosity and lubricant friction also tend to be proportional. In this study, the correlation between the speed and the friction was analyzed by changing the engine speed while fixing the combustion load and ignition timing. The friction tends to increase as the speed increases, but it was confirmed that the friction in the compression stroke was measured similarly, which was estimated as a composite result due to the change in combustion pressure. Also, as a result of analyzing the correlation between temperature and friction by changing the engine temperature, it was

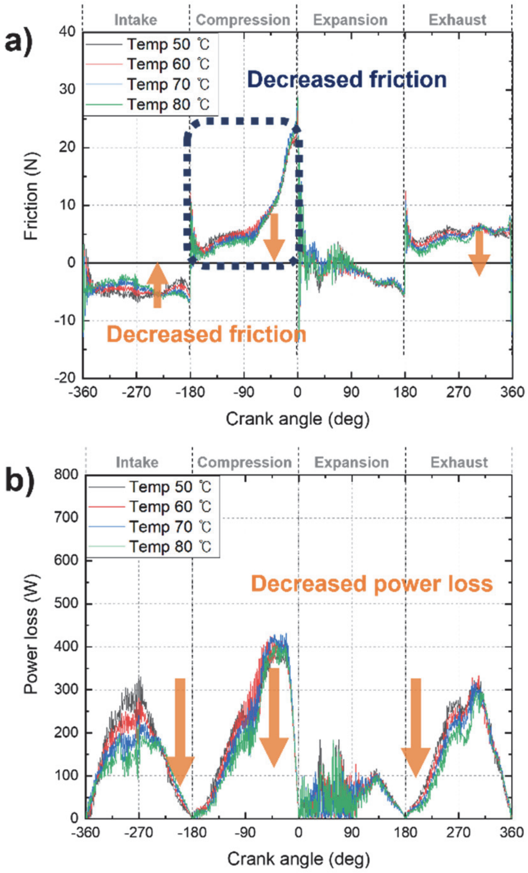

Figure 15. Comparison of a) Piston friction and b) Power loss due to increased temperature.

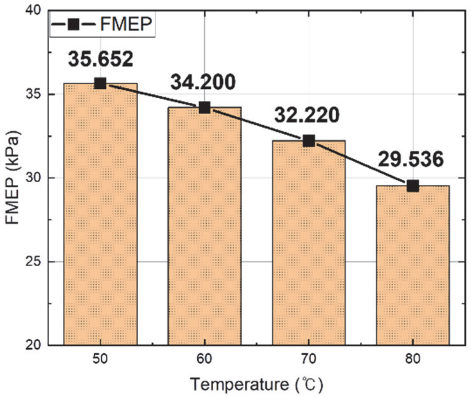

Figure 16. FMEP calculated from friction force by coolant/oil temperature.

confirmed that the friction decreased because of the decreased viscosity due to the increase in temperature. Therefore, from this experiment, it can be concluded that the lubricant conditions are factors affecting piston friction.

4. CONCLUSION

This study aims to investigate the characteristics of piston friction when the combustion conditions of an engine are changed. To measure the combustion friction of the engine, the experiments were conducted with a single-cylinder engine using the floating liner method. The combustion chamber pressure and the lubricant friction were set as factors affecting piston friction, and experimental variables for each factor were determined. The combustion load and the ignition timing were determined as variables affecting combustion chamber pressure, and the engine speed and the coolant/oil temperatures were determined as variables affecting lubricant friction. From the friction data acquired by varying each experimental variable, the following conclusions can be drawn:

(1) To confirm the effect of combustion pressure on the piston friction, the frictional force was compared by fixing other experimental variables and adjusting the combustion load and ignition timing. As a result of the experiment, it was measured that the frictional force increased as the combustion load increased, and it was confirmed that the friction decreased due to the delay of the ignition timing. Since the engine speed and temperature were kept the same, the lubricating friction was maintained the same. Therefore, it was determined that the friction exhibited a characteristic proportional to the combustion load. In addition, it is possible to derive a friction reduction method through the delay of the ignition timing, but from the viewpoint of combustion, the combustion efficiency decreases as the ignition timing is delayed.

(2) To analyze the effect of lubrication conditions on the piston friction, the frictional force was compared while controlling engine speed and temperature. As a result of the experiment, it was confirmed that the friction loss increased as the engine speed increased. In addition, it was confirmed that the friction decreased as the engine temperature increased. As can be seen from the Stribeck curve, which is an indicator of lubrication properties, lubricant friction is proportional to the oil viscosity and the relative velocity between the objects and inversely proportional to the normal force. Therefore, it was confirmed that the lubricating friction increased due to the increase of the lubricant parameter value due to the increase in the engine speed. Likewise, Since engine oil has a lower viscosity as the temperature increases, the engine temperature is inversely proportional to the lubrication parameter. This demonstrated why the combustion efficiency was measured to be low at the cold start of the engine.

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